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Seasonal and interannual variability in runoff from the Werenskioldbreen catchment, Spitsbergen

Elżbieta MAJCHROWSKA[1] , Dariusz IGNATIUK [1], Jacek JANIA[1],
Henryk MARSZAŁEK[2] and Mirosław WĄSIK[2]

[1] *Uniwersytet Śląski, Wydział Nauk o Ziemi – Centrum Studiów Polarnych, ul. Będzińska 60, 41-200 Sosnowiec, Poland*

[2] *Uniwersytet Wrocławski, Instytut Nauk Geologicznych, pl. M. Borna 9, 50-204 Wrocław, Poland*

<elzbieta.majchrowska@us.edu.pl> <dariusz.ignatiuk@us.edu.pl> <jacek.jania@us.edu.pl>
<henryk.marszalek@ing.uni.wroc.pl> <miroslaw.wasik@ing.uni.wroc.pl>

Abstract: The results from a hydrological monitoring program of Breelva basin (Spitsbergen, Svalbard) have been analysed to improve the understanding of the Werenskiöld Glacier system's functioning in the High Arctic. Hydrographs of a 44 km^2 river basin (27 km^2 of which was covered by a glacier) were analysed for the period 2007–2012. Seasonal discharge fluctuations were linked to glacier ablation and meteorological parameters, including atmospheric circulation types. A dichotomy was found in the discharge peaks generation during the hydrologically active season, with the main role played by snow and ice melt events during its first part and the rainfall regime dominating its second part. Foehn type strong winds played a significant role in the generation of ablation type floods (*e.g.* in August 2011). A simple classification of the runoff regime was applied to the examined six-year period, resulting in the identification of its three types: the ablation type (dominant in 2007 and 2009), the rainfall type (in the years 2011–2012), and the mixed type (during 2008 and 2010). According to publications the river flow season in Spitsbergen begins in June and end with freeze-up in September or at the beginning of October. Recently, this season for Breelva tend to be extended with the mid-May onset and end in the second part of October. A multiannual trend was noted that reflects a growing importance of rainfalls, especially in September. Rainfall waters play a more distinct role in outflow from the Breelva catchment recently.

Key words: Arctic, Spitsbergen, Werenskioldbreen, discharge variability, rainfall and ablation regimes.

Introduction

The climate warming in the Arctic (ACIA 2005; IPCC 2007) affects the water cycle in both glacierized and unglacierized basins. Changes in hydrological processes in the Arctic have a number of significant implications related to freshwater supply and sediment transport to the sea, nearshore marine ecosystems, changes in landscape and land ecosystems. A better understanding of the hydrology of glacierized catchments is also important for studies of glacier processes (*e.g.* Willis 2005), with special reference to their dynamics linked to the functioning of the internal drainage system, and to the anticipation of future changes.

The Arctic hydrological cycle is dominated by physical factors that include snow cover, glacierice, permafrost and seasonally frozen soils, as well as wide annual fluctuations in the surface energy balance (Kane *et al.* 1991). The principal source for surface runoff in polar catchments is water from snow, ice melt and rain. They are strongly influenced by meteorological conditions (Killingtveit *et al.* 2003) and hence reflect climatic changes.

The already published results from Svalbard runoff (*e.g.* Peterson 1994; Hodgkins 1997) indicate that the climate warming leads to an increase in outflow from glacierized catchments, due to increased snowmelt and ice-melt volumes and a higher sum of precipitation. A prolongation of the outflow season is also reported as a result of climate change, with an increasing importance of shoulder seasons and winter rainfall (*e.g.* Nowak and Hodson 2013). Both effects are caused by higher air temperatures and the increased precipitation observed in Svalbard (Hanssen-Bauer 2002; Førland and Hanssen-Bauer 2003; Łupikasza 2013). While higher runoff from glaciers is a widely recognised effect of climate warming (Oerlemans 2001; ACIA 2005; Adalgeirsdóttir *et al.* 2006; Irvine-Fynn *et al.* 2011; SWIPA 2011), the importance of higher sums of liquid precipitation for the hydrology of Arctic catchments has been explored to a smaller extent (Bamber *et al.* 2004; Nowak and Hodson 2013).

In this context, the purpose of our paper is to analyse the importance of melting and rainfalls as the main components of the water balance for the hydrology of high-Arctic glacierized catchments. The study focus on the elements of the runoff from the basin and discharge variability on seasonal and interannual time scales.

Hydrological data from the Arctic are sparse, even in the relatively well-studied Svalbard Archipelago, where only five stations are continuously recording river stage and discharge (Sund 2008). Data from catchments of larger glaciers are particularly rare, despite their relative importance in predicting trends of future large-scale hydrological changes. The Werenskioldbreen example studied here during the period 2007–2012 will both fill this monitoring network gap and represent the yet hydrologically underexplored southern part of Svalbard. The field measurements will be supported by meteorological data analysis in order to determine the temporal variability in outflow from Werenskioldbreen and its major components. As a result, we aim to improve the understanding of the influence of climate warming on the water cycle in the European High-Arctic.

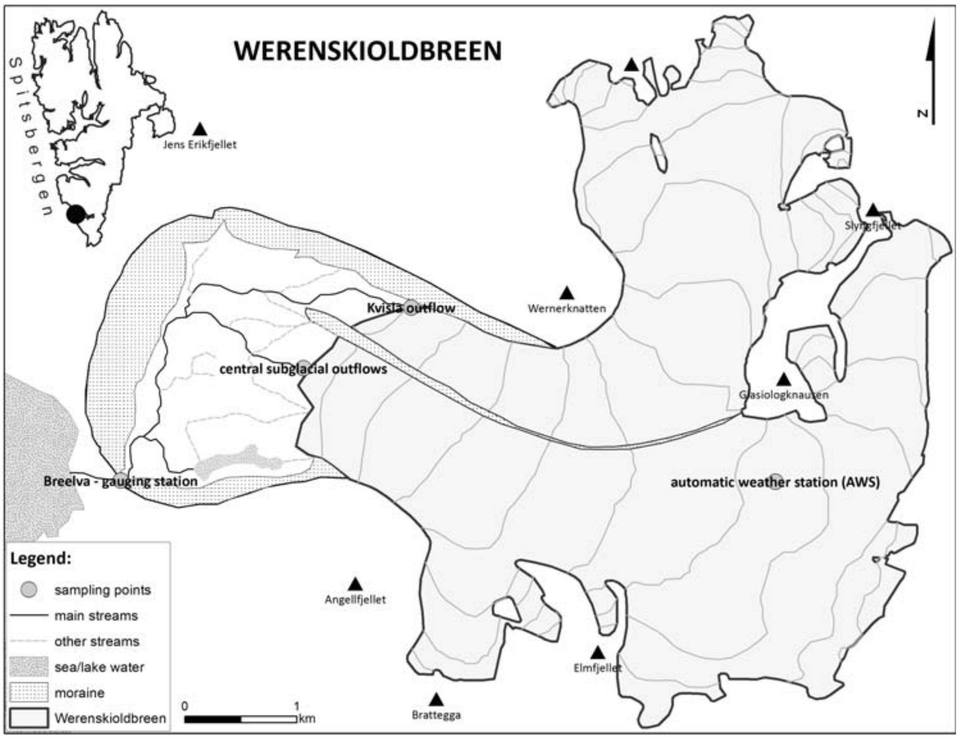

Fig. 1. The study area of Werenskioldbreen catchment. The gray dots indicate the location of the gauging station and main outflows (based on the map of Norsk Polarinstitutt, http://toposvalbard.npolar.no/).

Study area

Werenskioldbreen (77°05' N, 15°15' E) is located in Wedel-Jarlsberg Land, SW Spitsbergen (Fig. 1). The glacier basin of 44.1 km^2 is glacierized in 61% (27.1 km^2; Jania 1988; Ignatiuk *et al.* 2014). Werenskioldbreen has a clearly defined catchment area. The glacier extends from the 40–60 m a.s.l. at its front to 650 m a.s.l. in the firn field (Grabiec *et al.* 2012), and consists of two main ice streams, separated by a medial moraine. The glacier thickness is around 100–140 m. The surface consists of a 50–100-m-thick layer of cold ice, with temperate ice below (Pälli *et al.* 2003). This valley-type polythermal glacier of 9.5 km length (Hagen *et al.* 1993) is terminating on land. The proglacial area is closed from the west by an ice-cored frontal moraine.

The first hydrological studies of the Werenskiold proglacial river (Breelva) were carried out by polar expeditions of the University of Wrocław, Poland in early 1970s (Baranowski 1975; Baranowski and Głowicki 1975; Piasecki and Pulina 1975; Głowicki 1982), while the glaciological observations within the catchment were made as early as in the 1950s (Kosiba 1958). The drainage system of Werenskioldbreen consists of supraglacial streams draining into moulins, and a subglacial reservoir with bulk meltwater emerging from a few subglacial outflows at the front (Pulina *et al.* 1999). All outflows merge in the proglacial area of Werenskioldbreen, forming the Breelva which flows through a gap in the frontal moraine located to the south. Several creeks from the south flow through the Mewie Lake (Makevatnet). Following substantial changes in the hydrological network of the proglacial area before 1970 (Kosiba 1982), the Breelva has been draining the entire Werenskioldbreen catchment, as opposed to the situation before with two drainage pathways.

According to Krawczyk and Pulina (1983) and Krawczyk and Opołka-Gądek (1994), the main outflow from the Werenskiold Glacier did not change in 1983, 1986, 1988 and 1993, and remained in the northern part of the glacier snout (Kvisla Cave). The 1986 summer season was exceptionally rich in water, as compared with other analysed years. At that time, another river flowed from the middle part of the catchment. This river was fed by ablation water and also by subglacial outflows (called Black and Second Black Spring). The southernmost stream (near Angellfjellet) flowed into the Mewie Lake (Makevatnet). In 1991 and 1998, four proglacial streams were active: the main stream flowed from the Black Spring, the second major stream originated in the Kvisla Cave, two streams flowed from the southern part of the glacier into the Mewie Lake located in the marginal zone, and only one stream flowed out of the lake and joined the Breelva (Leszkiewicz *et al.* 1999; Pälli *et al.* 2003). The reported changes in the location of major outflows from the glacier, and consequently in the pattern of the proglacial rivers, did not affect the only drainage route out from the basin via a gorge across the frontal moraine located in the SW part of its arch. Since the 1970s, the main drainage stream from the Werenskiold Glacier has been the Breelva and it has been continuously gauged inside a channel cut in bare rock. This provided a major advantage for the runoff monitoring of the entire catchment.

Methods

The hydrological data discussed in this paper were collected at the Breelva gauging station between 2007 and 2012 (Fig. 1). The gauge is located just below the bend of the river in the frontal moraine (Fig. 2), *ca.* 1.6 km from the glacier front. The stage was automatically recorded on the left side of the Breelva channel, at 10-minute intervals, with the following two loggers, interchangeably: a CTD Diver DI 261 or a Mini-Diver (Schlumberger), barometrically compensated using data from a BaroDiver logger (Schlumberger). Every year in the study period, the discharge was measured using velocity area wading method (Herschy 1999) and the Seba F1 Current Meter for data collection. The rating curves of discharge *versus* stage consisted of 10–54 points per year ($R^2 = 0.87$ to 0.99). Finally, total runoff in the ablation season was calculated on the basis of the 24h running average of the water level and a rating curve. The start and end dates of the direct monitoring

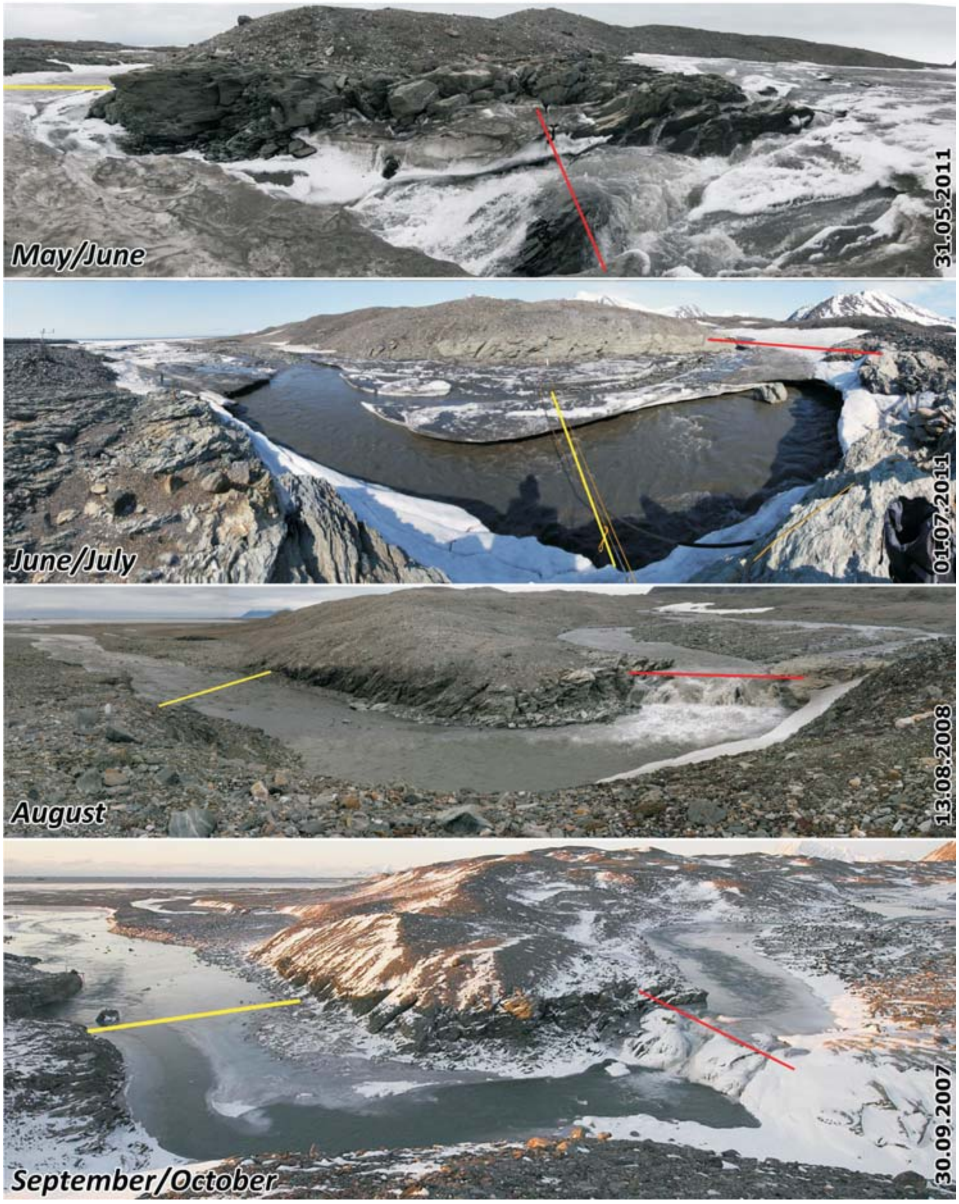

Fig. 2. Measurements of the Breelva (natural closure of the catchment) in different periods of the ablation season (red line – closure of the catchment, yellow line – gauging site).

of discharge were determined by the logistical constraints of the particular expedition. For technical reasons, a lack of data appeared in the data sets, especially with respect to low water levels in the Breelva. Missing data were completed with the use of the Deterministic Modelling Hydrological System (DMHS). The model was developed by Vinogradov *et al.* (2010) for application in all types of flow regimes

Table 1

Statistical characteristics of runoff simulations in the Breelva catchment with the DMHS method. RE – relative error [%] – the deviation between simulated and observed data, MPE – mean percentage error [%] – the average percentage error of the model fit.

Year	Simulated [10^6 m^3]	Observed [10^6 m^3]	Observed runoff relative to the total runoff [%]	Fraction of the ablation season [%]	Observation period	RE [%]	MPE [%]
2007	43.7	37.5	77.5	47.0	7.07–7.09	+16.5	27.5
2008	47.0	43.5	56.0	35.3	14.07–13.08, 3.09–24.09	+8.2	6.1
2009	45.2	51.7	57.3	44.3	2.07–16.08, 21.08–6.09	-12.6	13.3
2010	29.9	28.8	38.2	26.6	25.07–15.08, 20–24.08, 6.09, 13–14.09, 17.09, 1–10.10	+4.1	9.3
2011	81.2	73.4	98.7	83.1	23.05–1.09, 9–29.09	+10.6	30.3
2012	28.9	25.4	29.3	22.6	19.07–23.08	+13.5	31.7

worldwide. It has a simple structure, can be used for watersheds of any scale, and for all landscape zones. The Hydrograph Model includes a representation of all other essential components of the terrestrial hydrological cycle. Most of the model parameters are observable landscape properties which can be estimated *a priori*, systematized and transferred to areas which have not been gauged, without calibration. The DMHS has not been tested in glacierized catchments except the study site. However, it has been successfully applied in a polar catchment in the permafrost zone (*e.g.* Lebedeva and Semenova 2013a, b). Table 1 contains the results of the modelling, with its estimated error. For the purposes of further analysis, field data were used. These were complemented with the information from the model, where observed and simulated data have a significant correlation ($\rho = 0.67$, $\alpha = 0.05$). Most of the largest flood data were observed directly. The beginning and the end of the ablation season was confirmed through direct observations in the field (in 2008, 2010 and 2011 seasons).

The meteorological data used in this paper were collected by the Polish Polar Station at Hornsund located 16 km eastward from the gauge station at the elevation of 9 m a.s.l. (Marsz and Styszyńska 2013 and Hornsund GLACIO-TOPOCLIM Database http://www.glacio-topoclim.org/).

The ablation data for Werenskioldbreen originate from direct measurements taken between 2010 and 2011. They were collected and calculated on the base of mass balance measurements on 9 ablation stakes and with the SR-50 ultrasonic distance meter at the automatic weather station (AWS), at the elevation of 231 m a.s.l. (Ignatiuk 2012). For the other seasons (2007–2009), data were obtained from the neighbouring Hansbreen, where mass balance measurements on stakes had been done since 1989 (Szafraniec 2002). The continuous ablation record from Hansbreen was collected using the same type of logging device as on Werenskioldbreen; the SR-50 was located near ablation stake No. T4, at a site equipped with an AWS (175 m a.s.l.). Correlation coefficient between Hansbreen and Werenskioldbreen for mass balance (2008–2012) is 0.71 and for SR-50 at the same altitude is 0.99.

Results and discussion

General characteristics of runoff in 2007–2012. — The runoff from the Werenskioldbreen catchment was measured between 2007 and 2012. The average annual runoff was approx. $80\pm14\cdot10^6$ m^3 in these years, which is equivalent to an 1800 mm layer of water (1281–2243 mm) from the catchment surface. Annual runoff sums in the hydrologically active periods are presented in Table 2 and illustrated in Fig. 3. In the glacial catchment discussed here, the ablation season lasted between mid-May to early June and the first to the second half of October (134 and 159 days, which amounted to 40% of the calendar year; Table 3, Fig. 4). Due to the thermal conditions, the Breelva freezes and stops its flow in winter, and the gauge section is then covered with thick snowdrift. Icing (naled ice) formed near the front of the glacier, as water continued flowing and from its snout during cold periods of the year (Baranowski 1982; Bukowska-Jania 2003), a relatively common occurrence on Svalbard (Bukowska-Jania and Szafraniec 2005). Pulina *et al.* (1984) estimated water volume in the glacier at the beginning of the winter season in 1979/1980 hydrological year as $3.6\cdot10^6$ m^3. Approximately 20 % (*i.e.* $0.7\cdot10^6$ m^3) of this volume drained, whereas the other part, 2.9 mln m^3, frozen within the glacier.

The majority of the annual runoff volume was released in a relatively short period of time (usually up to 20 days, *i.e.* 10% of the year; Fig. 4). Moreover, peaks in

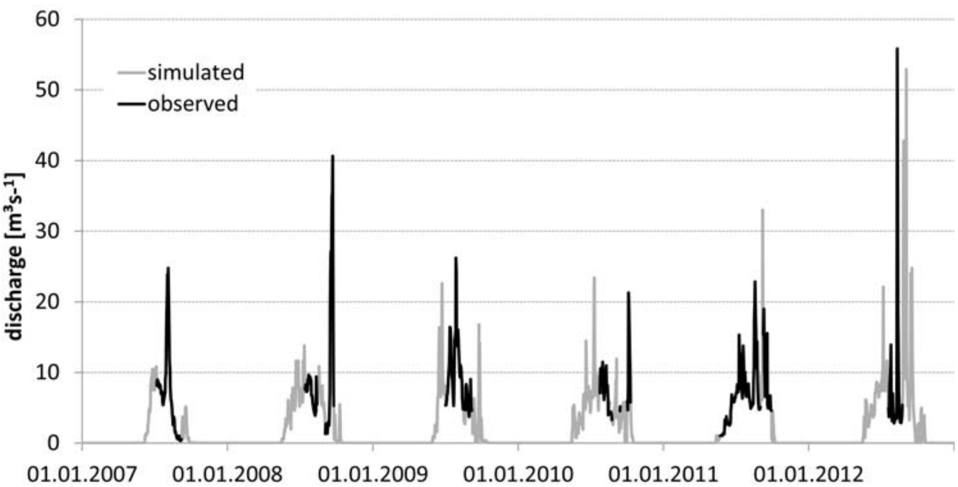

Fig. 3. Mean daily discharge from the Werenskioldbreen catchment at the Breelva gauge (black – measured, grey – simulated by the DMHS model).

Table 2. Runoff from the Werenskioldbreen basin: A – volumetric [10^6 m^3], B – water equivalent [mm w.e.], calculated for the whole catchment area.

A

Month	Year					
	2007	2008	2009	2010	2011	2012
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	2.09	0.08	3.66	1.46	3.96
6	10.19	15.94	17.06	14.24	10.45	15.28
7	21.98	21.67	30.03	23.67	23.24	22.63
8	20.04	16.97	20.84	16.22	23.85	30.10
9	4.09	26.32	10.39	10.56	22.14	23.80
10	0.06	1.06	0.51	10.00	1.13	2.92
11	0	0	0	0	0	0
12	0	0	0	0	0	0
[10^6 m^3]	56.37	84.04	78.91	78.35	82.28	98.71

B

Month	Year					
	2007	2008	2009	2010	2011	2012
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	47	2	83	33	90
6	232	362	388	324	238	347
7	499	492	683	538	528	514
8	455	386	474	369	542	684
9	93	598	236	240	503	541
10	1	24	12	227	26	66
11	0	0	0	0	0	0
12	0	0	0	0	0	0
[mm]	1281	1910	1793	1781	1870	2243

discharge were unevenly distributed across the active flow seasons, with flood events occurring at variable times and being of different origin during particular summer seasons (see Fig. 3).

Seasonal variability of discharge. — The water circulation in a glacierized catchment can be influenced by a number of factors, variable in time. The discharge under polar conditions is mainly driven by the rate of snow and ice ablation

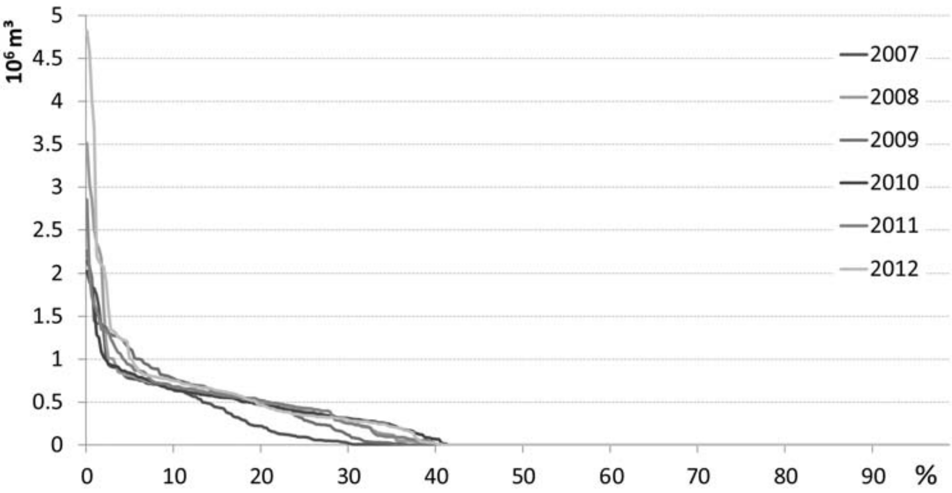

Fig. 4. Flow duration curves (FDCs) for the Werenskioldbreen catchment in the period 2007–2012.

which, in turn, is a result of variations in the air temperature (Fountain 1996), and modified by intensive rainfalls, causing high discharges or floods. Other factors, *e.g.* water storage in the glacier system and evaporation (less than 100 mm/yr – Killingtveit *et al.* 2003; 140 mm/yr – Szczepankiewicz-Szmyrka 1981) could also be considered, but they are very difficult to quantify and for smaller glacierized basins in Svalbard they are of minor importance. Therefore, only ablation and rainfall runoff regimes are taken into account in this study.

Air temperature variability might be reflected in discharges of the Breelva through its impact on the intensity of snow and ice melt. A relatively strong and significant correlation was found between the mean daily air temperatures measured at the Hornsund Station, and the daily discharges at the Breelva gauge ($R^2 = 0.49$, $\rho = 0.65$, $\alpha = 0.05$). Peaks of high discharges from rainfall events were superimposed on the discharge of ablation origin. Selected weather parameters (air temperature, precipitation) and snow depth at the shore meteorological station as also abla-

Table 3

Duration of the active hydrological season, according to the observations (2008, 2010, 2011) and the model (2007, 2009, 2012).

Year	Start date	End date	Duration [days]
2007	June 6	October 17	134
2008	May 17	October 13	150
2009	May 31	October 17	140
2010	May 16	October 16	154
2011	May 13	October 7	148
2012	May 16	October 21	159

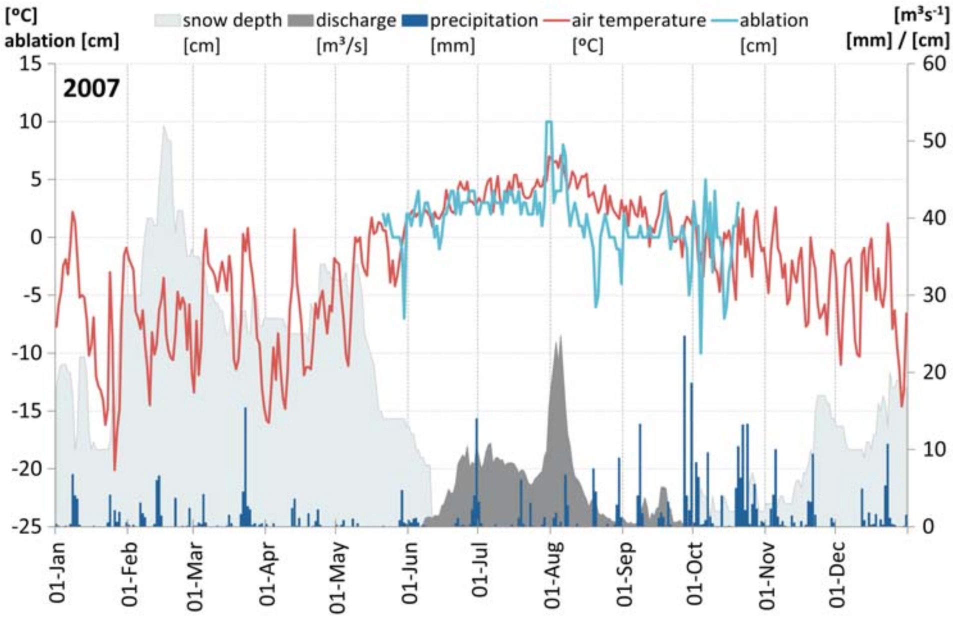

Fig. 5. Discharge at the Breelva gauge and the meteorological conditions, snow depth at the shore meteorological station and ablation parametr at Hornsund in 2007 (HORNSUND GLACIO-TOPOCLIM Database http://www.glacio-topoclim.org/ and authors' data).

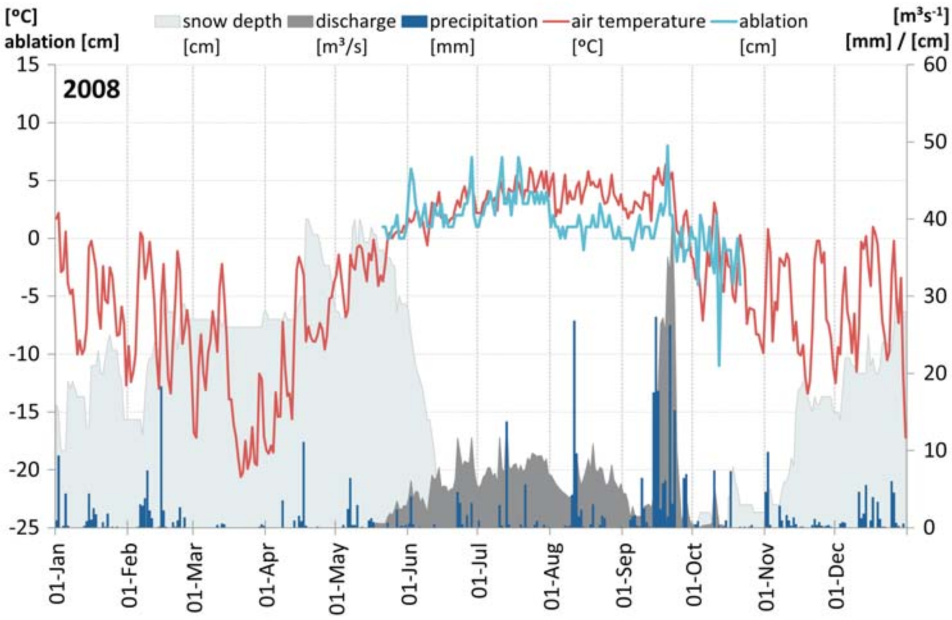

Fig. 6. Discharge at the Breelva gauge and the meteorological conditions, snow depth at the shore meteorological station and ablation parametr at Hornsund in 2008 (HORNSUND GLACIO-TOPOCLIM Database http://www.glacio-topoclim.org/ and authors' data).

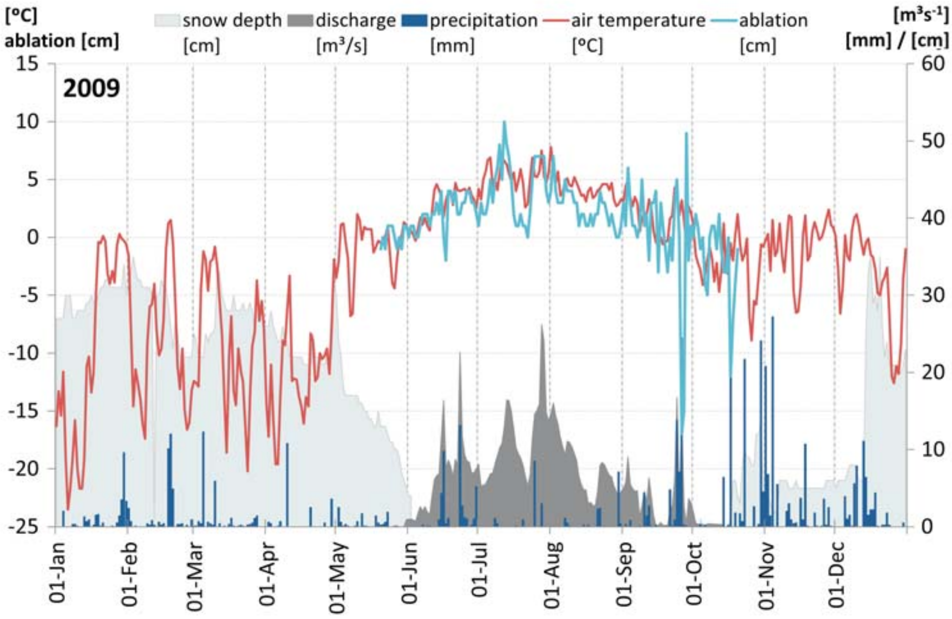

Fig. 7. Discharge at the Breelva gauge and the meteorological conditions, snow depth at the shore meteorological station and ablation parametr at Hornsund in 2009 (HORNSUND GLACIO-TOPOCLIM Database http://www.glacio-topoclim.org/ and authors' data).

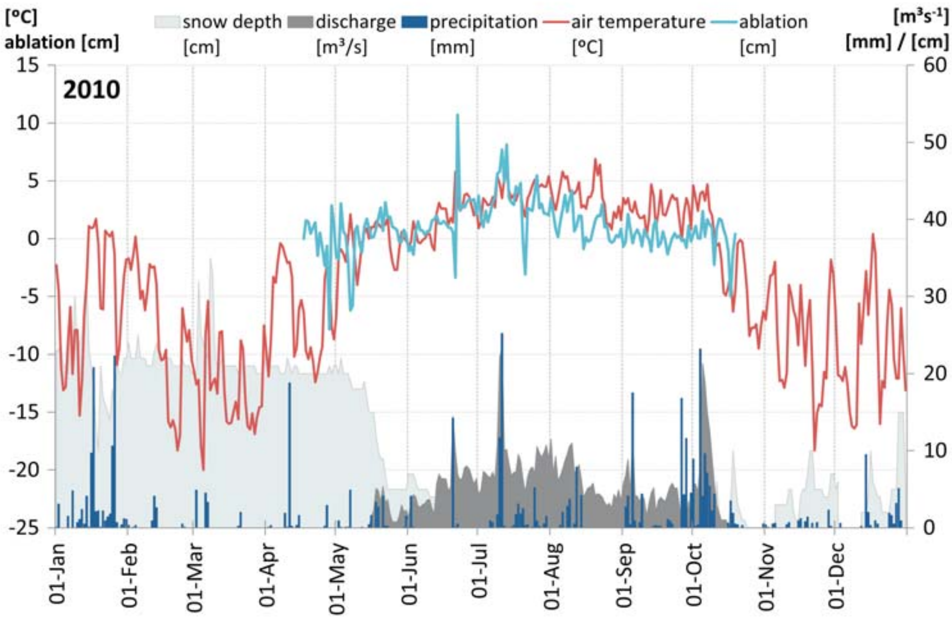

Fig. 8. Discharge at the Breelva gauge and the meteorological conditions, snow depth at the shore meteorological station and ablation parametr at Hornsund in 2010 (HORNSUND GLACIO-TOPOCLIM Database http://www.glacio-topoclim.org/ and authors' data).

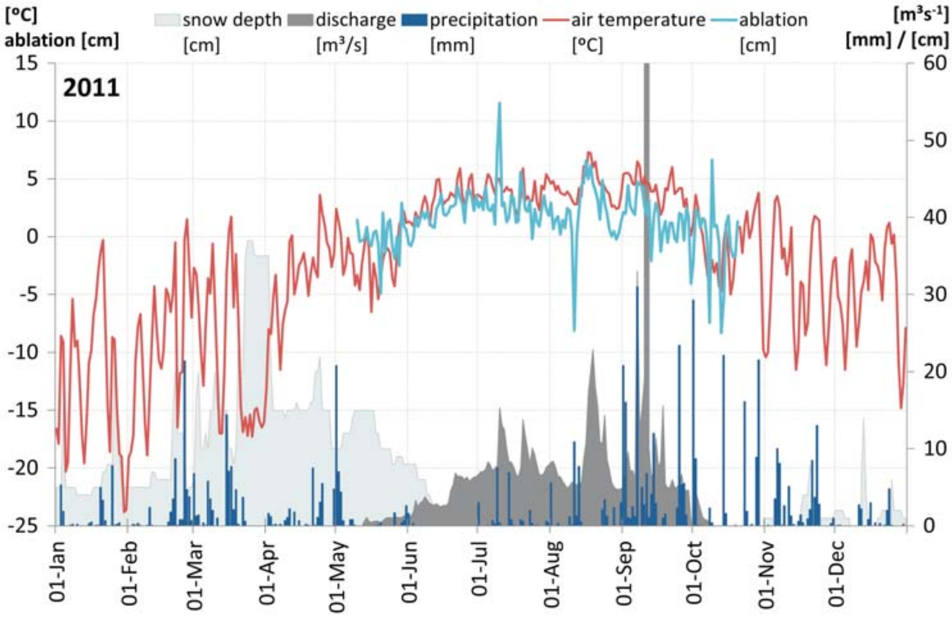

Fig. 9. Discharge at the Breelva gauge and the meteorological conditions, snow depth at the shore meteorological station and ablation parametr at Hornsund in 2010 (HORNSUND GLACIO-TOPOCLIM Database http://www.glacio-topoclim.org/ and authors' data).

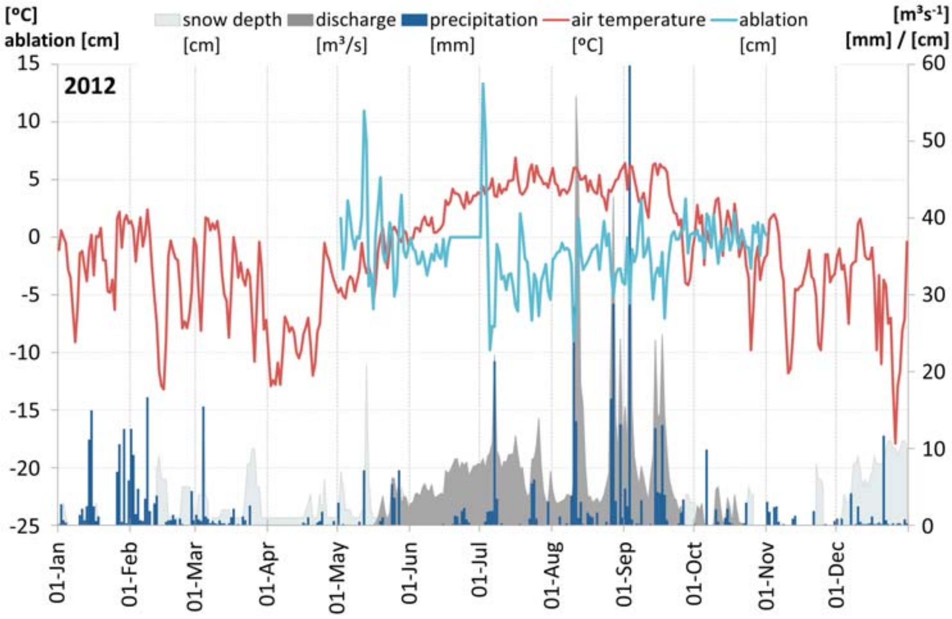

Fig. 10. Discharge at the Breelva gauge and the meteorological conditions, snow depth at the shore meteorological station and ablation parametr at Hornsund in 2012 (HORNSUND GLACIO-TOPOCLIM Database http://www.glacio-topoclim.org/ and authors' data).

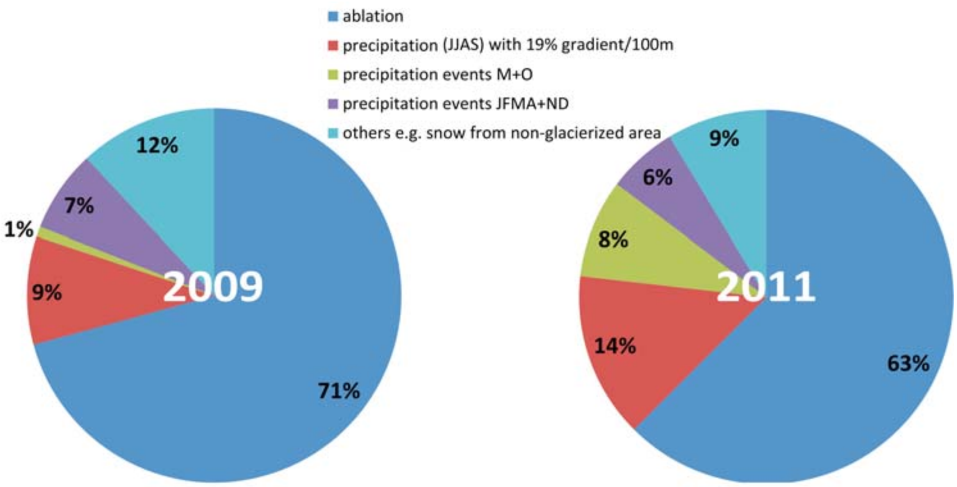

Fig. 11. The percentage contribution of water originating from various sources to the runoff from the Werenskioldbreen basin and periods of total runoff thereof in 2009 and 2011, respectively.

tion parameter are compared with the discharge of the studied river (Figs 5–10). They show the weather conditions to have a strong influence on the discharge curves every year. The Breelva flood events corresponded to an increase in the air temperature or to the amount of rainfall, or to both of these factors. Furthermore, the commencement of drainage coincided with the quick thawing of the snow cover.

In a significant part of the glacierized catchment water is produced by ablation of snow and ice. The mass balance of the Werenskiold Glacier was studied in 2009 and 2011 (Ignatiuk 2012). Across both years, ablation water constituted 62–71% of the recorded discharge. Precipitation water in the summer season (June–September – JJAS), with a precipitation gradient correction of 19% per 100 m of altitude (Nowak and Hodson 2013), accounted for 9% and 23% of runoff sums in 2009 and 2011, respectively. The rain occurring in May and October (MO) amounted to 1% and 8% in 2009 and 2011, respectively, and contributed to the formation of runoff in distinct episodes. Furthermore, winter liquid precipitation (November–April, *i.e.* JFMA+ND) formed 7% and 6% of runoff in 2009 and 2011, respectively. However, as evidenced by field observations, its ultimate removal from the system followed a period of englacial and subglacial storage, or the incorporation into naled ice. The remaining part of runoff was classified as "others", *e.g.* as originating from snowfall on the surface of the non-glacierized catchment (Fig. 11). The discharge peaks or flood episodes are associated with high ablation periods or intense rainfalls which strictly depend on meteorological conditions, and these are related to atmospheric circulation over the area. High ablation episodes appear during clear sky conditions and positive air temperatures (Ignatiuk 2012), but the most intense melting periods are usually related to the foehn-type eastern winds generating very high air temperatures, due to the passing of air

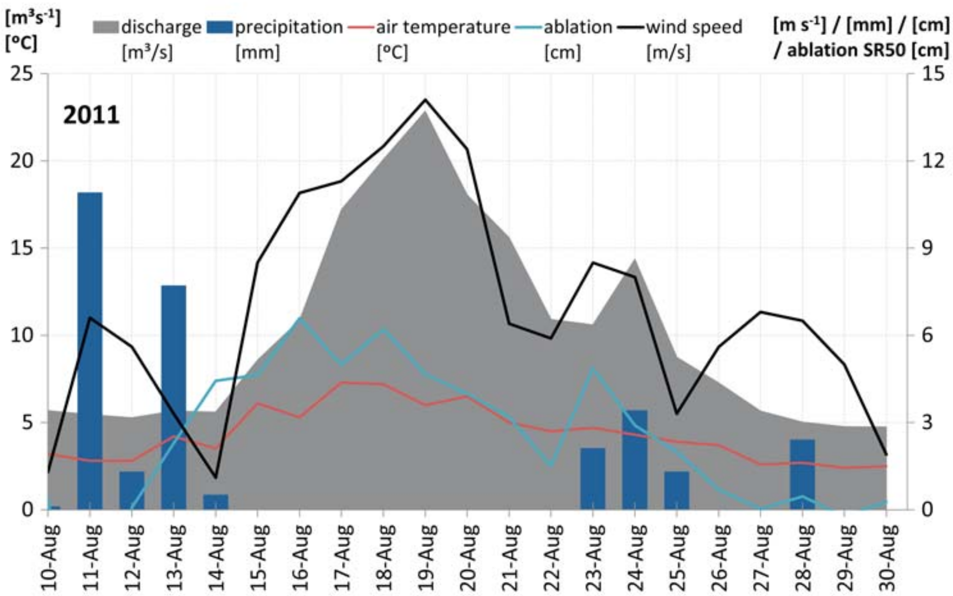

Fig. 12. Example of the influence of foehn-type winds on floods between 15th and 25th August 2011, when SE a was the dominant atmospheric circulation type (Niedźwiedź 2013).

through relatively high (700–1000 m a.s.l.) N-S mountain ridges eastward from the studied basin (Migała *et al.* 2008). Foehn-type winds are generated in a characteristic atmospheric circulation pattern, with a high pressure centre located on the eastern side of S Spitsbergen, and an atmospheric low in the western sector on the Greenland Sea. During the foehn events, melting increases, particularly when the low pressure system centre approaches Hornsund. In such circumstances, pressure gradients become higher, which magnifies the wind velocity and after crossing the orographic barrier causes increase in air temperature as adiabatic warming effect on windward side. As a consequence, water discharge from the glacier raises significantly (Fig. 12). In the end of the foehn episode, a rain period very often appears as a result of the atmospheric front passing as part of the low-pressure area. Therefore, immediately after high ablation, pluvial runoff regime also appears in Breelva. Other heavy rain periods are not necessarily linked to the previous foehn-type weather, nevertheless they are related to the prevalent atmospheric circulation.

Niedźwiedź (2013) introduced a 21-type classification of atmospheric circulation, to quantify the impacts of high- and low-pressure situations on southern Spitsbergen, and this classification was used here in the analysis of flood origin. The highest floods with discharges exceeding 7 $m^3 s^{-1}$ (above average discharge) and reaching up to 56 $m^3 s^{-1}$ in the period 2007–2012 were selected and analysed. Their occurrence was related to the inflow of warm air masses from the southern sector (directions SE, S and SW). Table 4 presents the individual types of floods

Table 4

Flood episodes on Breelva: their runoff regime, prevalent atmospheric circulation type at the time, the runoff sum of their duration and their contribution to the annual runoff (in %).

Runoff regime	Dominant type of circulation	Year	Period	Runoff [10^6 m^3]	%
ablation	SEc	2007	31.07–8.08	16.71	30
rainfall	SWc	2008	13–23.09	22.19	26
ablation	SEa, SWa, Ka	2009	24.07–11.08	23.13	29
ablation-rainfall	Sc	2010	8–12.07	6.28	8
rainfall	SWc, Sc	2010	26.09–9.10	9.18	12
ablation	SEa	2011	15–25.08	13.64	17
rainfall	Sc, SEc	2011	3–11.09	10.35	13
rainfall	SEc, SWc	2012	24.08–4.09	20.43	21
rainfall	SEc	2012	12–18.09	9.56	10

Key to circulation types: all acronyms ending with "c" denote cyclonal situations, while those with "a" in the end describe anticyclonal situations. Capital letters show the predominant air advection direction, *e.g.* SEc is a cyclonal circulation situation with air advection from south-east. Ka means a high-pressurewedge or ridge.

matched with the circulation types (Niedźwiedź 2013) predominant during their occurrence. The volume of evacuated water during flood events increases in the second half of August, in September and in October, which is linked to the advection of air masses from the south. This circulation type is introducing both high rainfall and ablation events. Precipitation-induced floods constituted almost 30% of the total annual runoff in 2008, while ablation was intensified at the end of July and at the beginning of August of 2007 and 2009. Ablation floods, occurring within about 10 days with warm air advection, constituted approximately 30% of the annual discharge in those years.

The ablation-induced high discharge events were generally more frequent in the first part of the runoff season, while later on during the season, flood episodes of rainfall origin dominated.

Based on the discharge variability during the analysed seasons (see Figs 5–10; Figs 13, 14), and the importance of melt and rain, main types of runoff regimes occurring during the flow seasons were distinguished high discharge episodes during late summer and autumn were typically of precipitation origin, while in the midst of the flow season, water more frequently originated from intense ablation. This division corresponded to the dominating types of atmospheric circulation in the hydrologically active period of certain years (Fig. 15). Expectedly, the southern inflow of warm air masses often brought heavy precipitation (Łupikasza 2013).

The frequency of occurrence of the circulation types corresponded well with the relative number of discharge peaks of different origin, and with the monthly runoffs from Breelva.

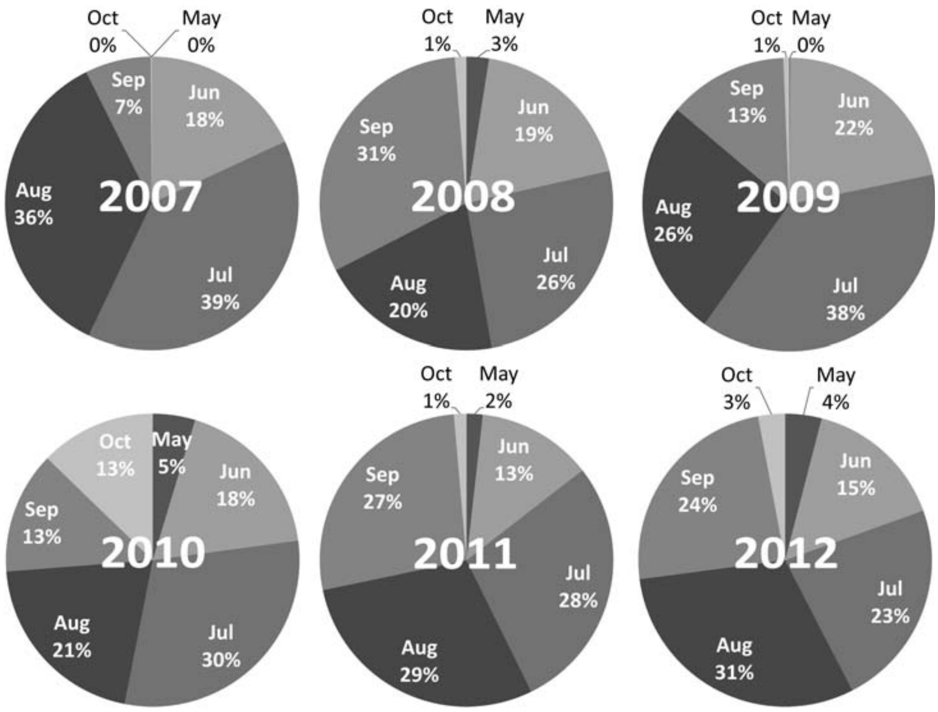

Fig. 13. Monthly contribution to the runoff from the Werenskioldbreen catchment in the analysed years.

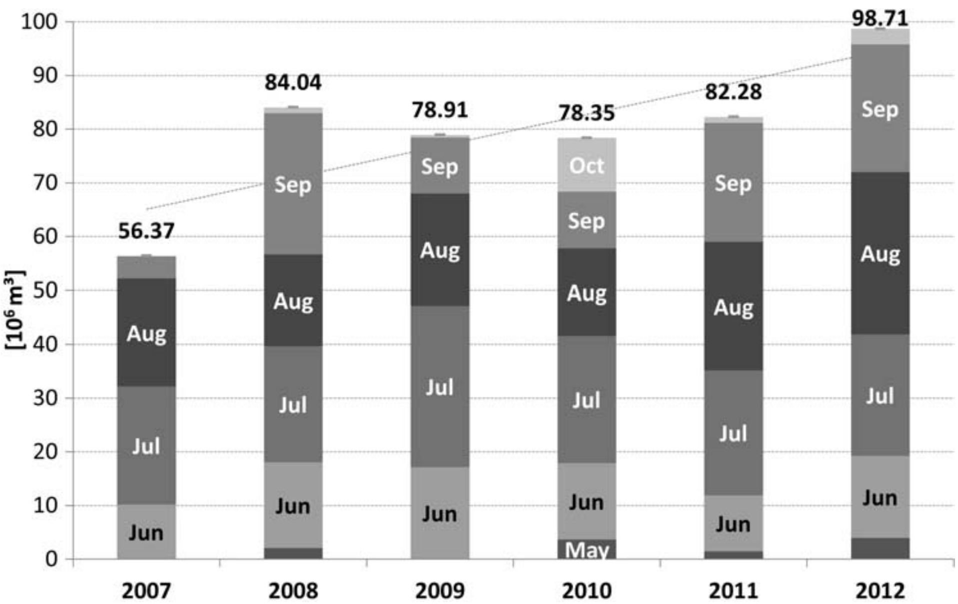

Fig. 14. Annual runoff from the Werenskioldbreen catchment divided into monthly contributions during the active flow seasons in the period 2007–2012. The linear trend of the total runoff is marked.

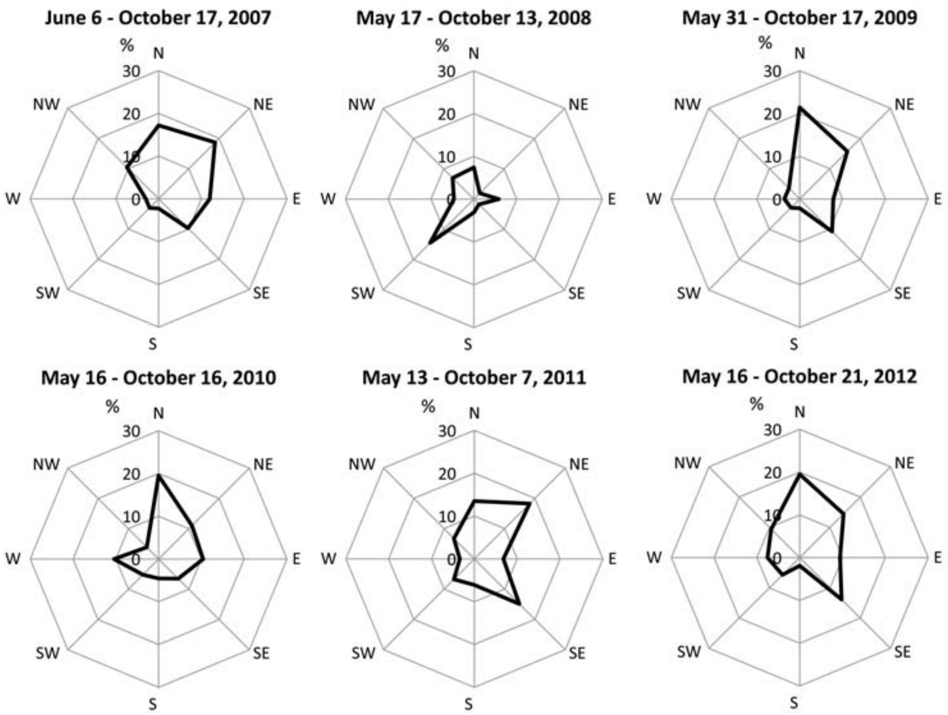

Fig. 15. Distribution of the relative frequency (in %) of atmospheric circulation types in southern Spitsbergen (Niedźwiedź 2013) during the active hydrological seasons in the Breelva catchment (2007–2012).

A classification of seasons is proposed here, that incorporates the predominance of one of the three major runoff regimes (ablation, rainfall and mixed type), as described below:

A – "ablation type", represented by the years of 2007 and 2009, with a few episodes of more intense melting in the beginning of the ablation period, and a prominent ablation peak at the turn of July and August, sometimes of the foehn-type origin. Such intense melting episodes constituted approx. 30% of the total annual runoff. Almost 40% of runoff in these seasons was noted in July. More than half of the seasonal discharge (64–76%) was took place in July and August. In these seasons, the most prominent feature was the prevalent atmospheric circulation from the N-NE-E sector (Fig. 15).

R – "rainfall type", typical for the 2011 and 2012 seasons, when a more intense runoff happened in the second part of the hydrologically active season (August–October), exceeding 50% of the total annual runoff. Large scale floods caused by precipitation appeared in the second half of the seasons, when drainage system is developed very well and rainy water can leave it very quickly. The single peak caused by precipitation even contains *ca*. 30% of the total runoff from the catchment. In these seasons were visible influence by atmospheric circulation from the SE-S-SW sector (Fig. 15).

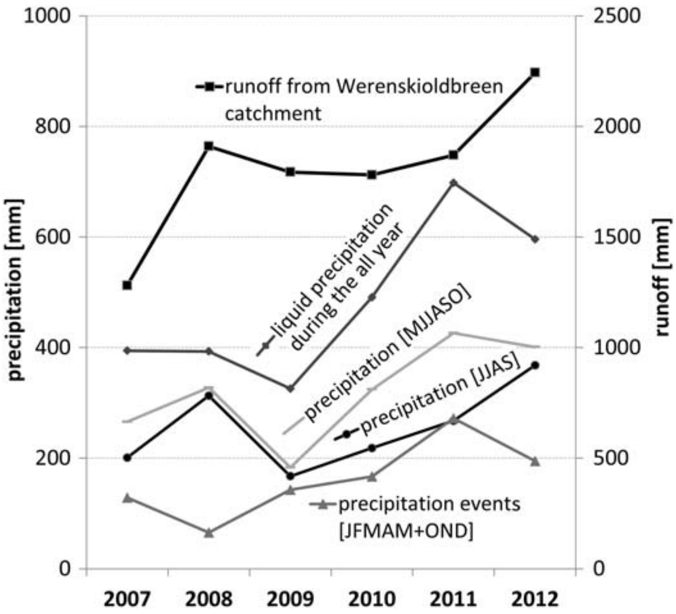

Fig. 16. The course of runoff from the Werenskioldbreen basin, compared to the liquid precipitation sums in various periods during 2007–2012.

M – "mixed type", with a balanced discharge during a rather cool ablation season, as noted in 2008 and 2010, however discharges in July and August constituted more than 50% of the annual runoff. Significant peaks in discharge or floods were noted towards the end of the ablation season in the second half of September, or even in October. Peaks at the end of the hydrologically active season were caused by atmospheric circulation from W or SW sectors (Fig. 15).

The presented regime types are based on the distribution of water discharge in the Breelva during the hydrologically active season, and on the dominant sources

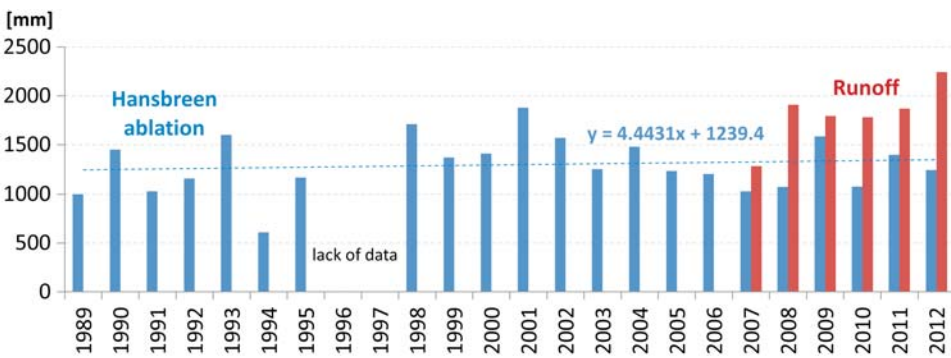

Fig. 17. The annual runoff from the Breelva catchment (2007–2012) in connection with the summer ablation of Hansbreen (mm of water equivalent) for the mass balance observation period (1989–2012).

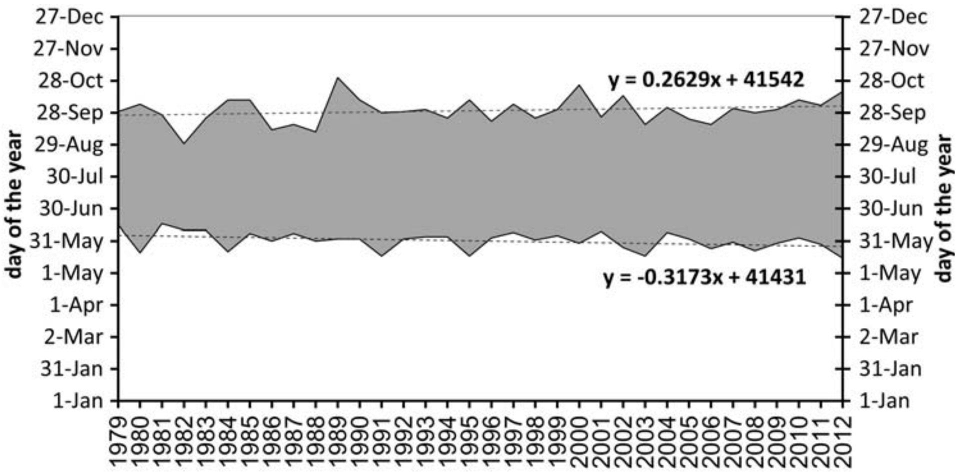

Fig. 18. The start and end dates of potential ablation seasons (*i.e.*, periods with positive mean daily air temperatures at the Polish Polar Station, Hornsund) during 1979–2012.

of water. In all types of the regime, liquid precipitation plays an important role. Despite the fluctuations in the annual precipitation, discharge peaks originated from rainfalls both in warm and cold periods of the year (Fig. 16). A significant contribution of rainfalls during the cold season (JFMAM+OND) to the total annual sum of liquid precipitation is visible; also, a growing share of this form of precipitation is noted in all seasons. Therefore, the importance of rainfall water with respect to the total discharge is increasing, consistently with observations from elsewhere in Svalbard (Nowak and Hodson 2013).

Interannual variability. — The trends of the hydrological processes in the analysed 2007–2012 observation period need to be treated with caution since the investigation period is very short. Nevertheless, some features could be observed. The total annual runoff from the basin undergoes significant interannual variations of up to 30%, as compared with the six-year average (79.78×10^6 $m^3 \pm 13.66 \times 10^6$ m^3, error margin reported as 1 standard deviation). The annual runoff value showed a tendency to increase during this period (Fig. 14). Such a strong positive trend could not be linked with an increased ablation of the glacier. The total runoff from the Werenskioldbreen catchment was compared with the summer ablation on Hansbreen (Fig. 17) due to a lack of mass balance data from the studied basin, and to a good correlation of the ablation data for these neighbouring glaciers when records existed. In the period 1989–2012, the summer ablation of Hansbreen showed a very small positive trend, and varied significantly from -53% to +45% of the multiannual average (1297 mm).

A negligible increasing trend in the glacier ablation was associated with a longer duration of the potential ablation season, as indicated by the date of first and last day with a positive mean air temperatures at Hornsund each year (Fig. 18). The

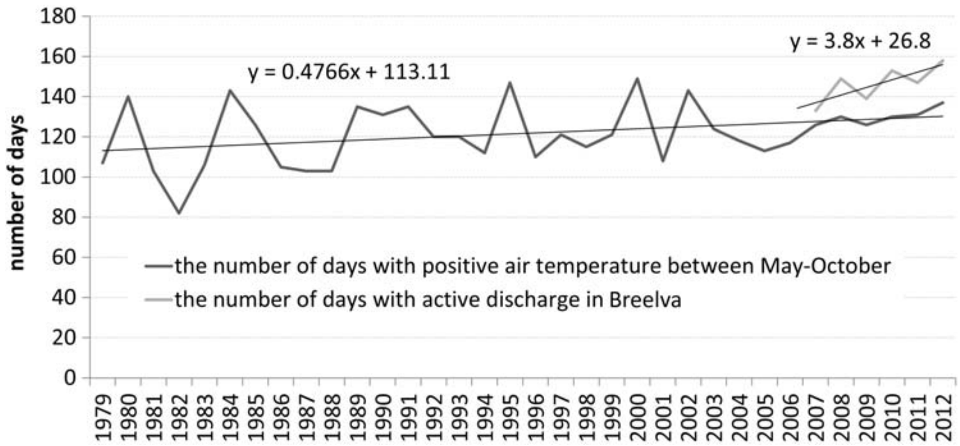

Fig. 19. The number of days with potential water discharge (days with positive air temperatures in Hornsund) and the number of days with observed discharge in the Breelva (including trendlines).

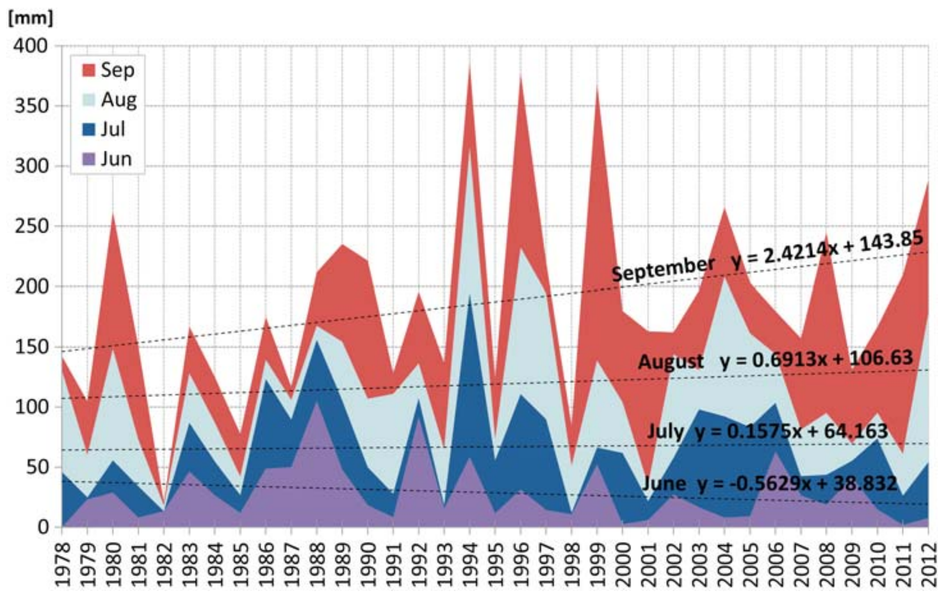

Fig. 20. Cumulative layered graph of precipitation at Hornsund during June–September (1978–2012).

trend towards an earlier commencement of the ablation period was more distinct than the slight trend prolonging the duration of melt (and runoff) in autumn. The duration of the period with positive air temperatures was used as a proxy for the duration of active water runoff from the basin. The number of days with discharge observed in the Breelva was higher than the number of days with positive air temperature (Fig. 19), due to the continued flow of water from the glacier and the active layer of permafrost during short spells of negative air temperatures at the be-

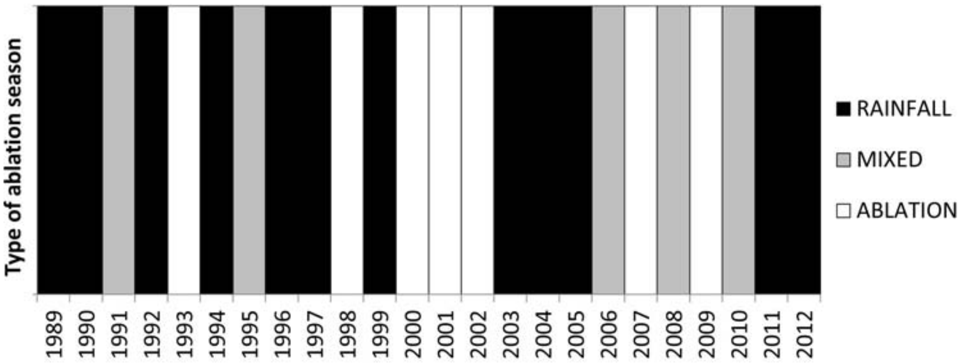

Fig. 21. Type of potential runoff regime during the ablation seasons 1989–2012: rainfall, ablation, mixed (according to the authors' classification and based on the ablation data for Hansbreen and precipitation between June and September at the Polish Polar Station, Hornsund).

ginning of the cold period. This could be further intensified by late rainfalls (Fig. 20). A modification of the occurrence and duration of the meteorological factors influencing the hydrological cycle was symptomatic for a modification of the water cycle due to the changing climate.

The lack of a significant correlation between the annual runoff values and the corresponding summer ablation, as well as the negligible trend in the multiannual course of the latter, suggest that liquid precipitation might be the driving factor for water discharge variability in the catchment.

A comparison of the runoff curve for 2007–2012 with the precipitation curve for summer months (JJAS) shows a relatively strong and significant correlation between these factor ($\rho = 0.74$, $\alpha = 0.05$). The annual rain sum has grown by up to 200–300 mm in this period. The amount of rainfall increased in the hydrologically active months (June–September) and to a smaller extent between October and May.

The potential runoff regimes were also classified for the period 1989–2012 (Fig. 21), using the summer ablation record from Hansbreen (Fig. 17) and rainfall data from the Polish Polar Station, Hornsund (Fig. 20). Seasons with above-average liquid precipitation between June and September (*i.e.* 200 mm) were considered of the rainfall type. When rainfall was less significant and below average, and the melting rate was above average (*i.e.* 1297 mm), we classified it as the ablation type. The mixed type was distinguished when no dominant type of water supply could be assigned to a given season. This simple classification showed that in the last 23 years, most seasons (n = 12) represented the rainfall regime. In the late 1990s and early 2000s, the ablation type seasons occurred more frequently (n = 7 in total). Earlier or later seasons with a predominance of melting snow and ice were preceded by a rainy or mixed season. After the early 2000s ablation years, there were three subsequent years dominated by precipitation (2003–2005), and so were the most recent, directly observed years 2011 and 2012. A clearly increasing trend

Table 5. Characteristics of the hydrologically monitored catchments in Svalbard, and their predominant types of runoff regime.

Name of the glacier or river	References	Area of the catchment [km^2]	Glacierized area [%]	Annual runoff [mm]	Period	Predominant type of runoff regime
Bayelva	Killingtveit *et al*. 2003; Sund *et al.* 2008	32	50	1612	1990–2001	62% – ablation
De Geerelva	Killingtveit *et al.* 2003; Sund 2008	79.1	8	539	1990–2001	not reported
Finster-walderbreen	Hodgkins *et al*. 2009; Cooper *et al*. 2011	65.7	66.2	1073	1999	ablation
Werenskiold-breen	this article	44.1	62	1800	2007–2012	2007, 2009 – ablation; 2008, 2010 – mixed; 2011, 2012 – rainfall
Waldemarbreen	Sobota 2013	5	50	541	1997–2010	55% – ablation
Erikbreen	Vatne *et al*. 1992	12.4	75	507	1990–1991	not reported
Scott Tunerbreen	Hodgkins 1997	12.8	32	499	1992–1993	not reported
Ebbabreen	Kostrzewski *et al*. 1989	51.5	52	300	1985 (part of the season)	not reported
Scottbreen	Bartoszewski *et al*. 2013	10.1	45.6	875	1988, 2005 (part of the season)	ablation

in the rainfall rate in September (Fig. 20) corroborates the growing contribution of precipitation water to runoff. The results of this simplified classification of runoff types shows an important role of liquid precipitation for hydrological processes in this glacierized catchment in Svalvard.

Comparison with other studies. — The magnitude of runoff in glacial catchments depends on the size of the glacier, the glacial cover percentage, and the course of thermal and radiative conditions during the ablation season (Baranowski 1975). A direct comparison of the results obtained for the Werenskiold Glacier with other data for Spitsbergen is difficult (Table 5). This is not only due to differences in observation period duration for each of the studied catchments, on the interannual and sub-annual scales, but also because the glacier area and its contribution to the size of the monitored catchments varied across study sites. Data on the proportions of ablation and rain water are often missing. A further complication is the thermal structure of these glaciers, affecting their water cycle and hence the runoff from the entire catchment.

The annual hydrological regimes of glacierized catchments in Svalbard are widely variable. Killingtveit *et al.* (2003) note that runoff is dominated by snowmelt in June and July, while in August and September it is mainly derived from rainfall and glacial melt. Research carried out on Finsterwalderbreen in 1999 indicates that the majority of precipitation was delivered during winter (226 mm), while the summer was rather dry (29 mm). The hydrological regime was partly dictated by the melting of snow and ice, as suggest Hodgkins *et al.* (2009). Comparable parameters have been observed at the Bayelva catchment which drains the Austre and Vestre Brøggerbreen glaciers located in the northwest of Svalbard, and which is so far the best studied glacierized catchment in Svalbard with longest series of direct observations. Hagen and Lefauconnier (1995) collected its discharge records for the period 1975–1978, whilst in 1989 the continuous monitoring of the river by the Norwegian Water Resources and Energy Administration (NVE) commenced. The average runoff from the studied catchment is 1612 mm, a comparable value to that registered in the Breelva catchment. According to Nowak and Hodson (2013), winter rainfalls contributed to an increase in both the variability and the duration of discharge, however neither the duration nor the magnitude of runoff has shown a significant trends over the last 35 years. Only in the last ten years was a slight increasing trend found in the volume of water leaving Bayelva catchment annually.

The hydrological trends in the Breelva catchment resemble closely those detected for Bayelva. The runoff from the catchment does not show any significant changes when compared with the data collected 30–40 years ago. For example, in 1980 the estimated runoff from the Werenskiöld Glacier catchment was 1876 mm (Leszkiewicz 1987). The annual sum of precipitation was then 594 mm, with a precipitation gradient correction of 19% for both snow and rain (Nowak and Hodson 2013). This value is comparable with the runoff in the period 2007–2012, ranging from 1281 to 2243 mm (about 1800 mm on average), and the contemporary precipitation sum of 634 mm with a 19% gradient. Leszkiewicz (1987) estimated the contribution of the ablation water to runoff from another glacierized catchment to be 1390 mm, *i.e.* 82.7% of the total runoff (1680 mm). In an attempt to balance the runoff from the Werenskioldbreen catchment in the seasons 2009 and 2011, it was established that the ablation runoff accounted to about 60–70% (Ignatiuk 2012), and in other seasons it seems to have been even smaller (according to ablation observations from Hansbreen, Fig. 17). This reduction in the contribution of ablation water requires further verification, but it may be a prerequisite for a growing importance of precipitation in the runoff from this glacierized catchment. The total volume of runoff has not changed significantly over the years, whilst seasonal discharges increased as a result of the meteorological conditions, particularly in the form of rain-induced floods of approx. 10 days duration, which may contribute approx. 30% of the annual runoff (see Table 4).

For other glacierized catchments, *e.g.* for the much smaller Waldemar Glacier, the average contribution of ablation water was 55% between 1979 and 2009 (Sobota 2013), whereas for a comparably sized Bayelva catchment this value was 62% (1990–2001; Killingtveit *et al.* 2003). This allows to look for other sources of outflowing water, *e.g.* in liquid precipitation as indicated in this study.

Conclusion

The runoff from the Werenskioldbreen catchment in the period 2007–2012 showed distinct variations, both during particular years and interannually. An increase in the number of high discharge and flood events during active runoff seasons was noted. A typical temporal development pattern could be distinguished: the discharge peaks during the first part of the summer season were usually linked to high ablation episodes, with maxima connected to foehn-type winds, and occurring at the end of July or beginning of August. Towards late summer, the number of flood events increased, including the autumn months, when peak flows of rainfall origin appeared more often. Furthermore, the frequency of winter rainfalls (*i.e.* in December, January and February) increased in the period 2007–2012. The weather conditions influencing these water discharge patterns are related to the types of atmospheric circulation: the ablation-related peak discharges are typically occurring when air masses come from N and NE, while the advection of warmer and wet air masses from the southern sector is responsible for heavy rain periods.

The temporal distribution of higher ablation and rainfall events and the proportions between both factors during active flow periods have driven a classification of seasons according to their runoff regime. During the study period, the different types of the hydrological regime were evenly distributed: 2007 and 2009 were classified as ablation type, 2011 and 2012 as rainfall type, and 2008 and 2010 as mixed type.

The total annual water runoff correlated significantly ($\rho = 0.74$) with the sum of precipitation in the summer months (JJAS), while no relationship was found between the total seasonal runoff and the ablation sum. Furthermore, despite the high interannual variability of the runoff regime types, a slight domination of rainfall type seasons could be noticed in the last decade, which resulted from a more frequent occurrence of heavy rainfall events at that time.

Despite the lack of trends in the total summer ablation values for the neighbouring glacier Hansbreen, a weak trend of increase in the duration of melt seasons could be observed. It was more noticeable at the onset of the melting season than for termination in the fall. The observed duration of the water flow in the Breelva has become distinctly longer recently, with a significant positive trend. It could be related to the drainage of rainfall waters from the heavy precipitation events in autumn.

A comparison of the Werenskioldbreen basin with other available glacierized catchments studied in Svalbard confirms the observed seasonal variability in discharges as being driven by meteorological factors, as well as shows the southern part of Spitsbergen to represent the highest values of runoff among the investigated basins in Svalbard. The results of other authors suggest that the main contribution to the total runoff in this archipelago is coming from melting snow and ice, although Nowak and Hodson (2013) indicate increasing importance of shoulder seasons and winter rainfall as a result of climate change.

The local topographic conditions the Werenskioldbreen basin, such as the westward orientation of the valley, with an open access for western and southern air masses, also seem to be responsible for the substantial share of rainfall water in the total runoff, despite the relatively large glacial coverage of the basin area (62%) . Furthermore, an increasing trend in liquid precipitation delivery has been noted for the whole Svalbard in the recent years (Førland *et al.* 2011). Therefore, a high seasonal variability of discharge in Svalbard is related both to heavy rainfall events and the high ablation events (with a contribution of the foehn effect). The long-term changes also reflect a slight increase of the rainfall waters share in the runoff production.

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